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Preprint of Paper Presented at the Sixth European Aeronautical Congress

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FOREWORD

/I

In this paper, the light aircraft classes, presumably in question for piston as well as for turbine engines, are statistically determined and classified. Here, with respect to aircraft weight and cruising speed, the upper limit was taken as that aircraft class for which the introduction of jet engines is a basic prerequisite for total conception. The lower limit, conversely, is given by the smallness of the required power plants which are extremely difficult to design as turbine engines. After a detailed analysis of the present state of the art of piston engines for the lower performance range and a brief preview over the development of turbine engines of the lower thrust and performance classes, the possibility is discussed of developing the turbojet engine on the basis of a supercharging blower drive with high bypass ratio; this drive, within the range of predetermined light aircraft classes, could effectively replace the piston engine as well as the turboprop engine which latter has some disadvantages. Therefore, main emphasis in this paper was placed on a discussion of the design and sizing of such a drive. The considerations led to a ducted-fan engine with a bypass ratio of about 6, which thus permits optimum cruising speeds of 500 - 550 km/hr and, at a minimum range of 1650 km, permits payload components comparable to piston aircraft. With a moderate amount of development work, ranges of 2000 - 2500 km will be completely within the range of possibilities. However, the problem of noise and the question of cost efficiency create some difficulties. A reduction in manufacturing cost can be obtained only by going into large-scale production. This could lead to the creation of a standard power plant which, marketed in only a few variants, could be used for a large number of aircraft prototypes.

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Analysis showing that a turbojet engine developed on the basis of a supercharging engine with very high bypass ratio should be superior to the piston and turbojet engines currently used in light aircraft. A discussion of the layout and rating of such an engine leads to a bypass configuration with a bypass ratio of roughly 6, capable of cruising at speeds between 500 and 550 km/hr with a payload comparable to that of equivalent piston engine aircraft.

author

Introduction

At a time at which billions are spent for new developments in the field of space travel and supersonic transport, it is rather anticlimactic to speak of the requirements of "general aviation" since the public is of the opinion that developments in this particular field have long since been concluded. However, a closer scrutiny of this topic shows that the development of light aircraft has by no means come to a conclusion but that numerous promising engineering problems must be solved here. These problems concern less the airframe itself than the engine construction.

One might say that the piston engine still is the most suitable propulsive system for a certain group of light aircraft and that, in this field of application, its reliability and economy, specifically with respect to cost, cannot be excelled by any other type of engine at the present state of the art of power

* Numbers in the margin indicate pagination in the original foreign text.

plant development. However, this can be contradicted by stating that, if some development work is done in this direction, the turbine engine will constitute just as suitable a propulsive unit which, in the form of a properly designed and dimensioned jet engine, has the great advantage of structural simplicity and low weight. Despite the fact, as mentioned elsewhere (Bibl.1, 2), no improvement possibilities for piston engines exist at present, it can be stated that possibilities for improving turbine engines are in existence; in our opinion, decisive improvement can be obtained by using the ducted-fan principle. One frequently encounters the opinion that a properly dimensioned dual-jet or - stated more concisely - a supercharged engine is definitely equivalent to a piston engine or even superior to it, specifically if mass production can be envisioned.

1. Classification of Light Aircraft with Respect to Selection of Engine Type /2

For our discussions, a few remarks should first be made with respect to the concept "light aircraft". In connection with considerations on the selection of engine type, light aircraft can be subdivided into various aircraft classes, which are mainly characterized by the takeoff weight of the aircraft and by its characteristic cruising speed (Bibl.3); Fig.1.

The field of aircraft classes for which, in addition to the conventional use of piston engines, the promising application of turbine engines is still in question, can be delimited, from the top downward, by jet-driven business touring aircraft with takeoff weights between 4 and 9 Mp*. These units, manufactured already in considerable numbers, show that the concept of jet-

* Mp = 1000 pond = 1000 lb, which will be used hereafter (Transl.).

propelled touring and business aircraft is a feasible and promising way, a fact which need not be further proved by actual calculations.

The delimitation of the application field from the lower weight classes is not quite as easy. However, it can be stated that for aircraft with a takeoff weight of 1000 lb, i.e., touring and sports aircraft, a replacement of piston engines by turboprop engines is hardly in question because of the bulky propeller control mechanisms required for turboprop engines; rather, a replacement by turbojet engines might be in question, in which the specific design of ducted-fan engines may have some promise. In this connection, mention should be made of investigations and projects in work at the BMW* at the end of the Fifties, which were concerned with a dual-flow engine having a bypass ratio above 2.5, to be used for light aircraft with takeoff weights of 1000-1500 lbs. Despite the fact that the calculations made at the BMW yielded positive results, it will be found that the required thrusts and performance for aircraft of less than 700 lb takeoff weight are too low to design fully acceptable jet engines which would be able to replace the piston engine in this particular aircraft class.

This leaves aircraft belonging to the class of more pretentious sports /3 and touring aircraft including small business aircraft whose takeoff weights are close to 1500, 2500, and 3500 lb. These include 4-seaters, 4 - 6 seaters, and 6 - 7 seaters as well as single- and twin-engine aircraft, in which case the lower weight class includes single-engine as well as twin-engine designs. The average values of some characteristics of these aircraft are shown in Table 1. Accordingly, the maximum cruising speed at 2 - 3.5 km altitude, depending on the weight class and number of engines, is 280 - 380 km/hr at an average 70% load ratio of the power plant. Depending on the payload requirement, these aircraft

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* BMW = Bayrische Motoren Werke (Bavarian Engine Manufacturers).

are designed for a range of 1000 - 1300 km or 2000 - 2500 km. The takeoff distances vary between 250 and 600 m.

The aircraft classes, compiled in Table 1, are representative for a large number of aircraft prototypes and thus also for prototypes manufactured on a relatively large scale. This indicates the presence of a correspondingly large demand, meaning that these particular aircraft classes are of special interest in connection with the question of novel engine concepts.

Between the field of large dual-jet business touring aircraft and the rather limited field of 1500 - 3500 lb aircraft with piston engines, there is the field of twin-engine turboprop aircraft with takeoff weights of 4000 - 2700 lb. Single-engine turboprop aircraft with takeoff weights between 1800 and 2300 lb are included in the field of twin-engine aircraft with piston power plants. In addition, a field of twin-engine jet business and touring aircraft with takeoff weights of 3500 - 4000 lb should be mentioned, directly following in line after the above-mentioned business aircraft with takeoff weights above 4000 lb. The present range of twin-engine turbine aircraft shows that the turbine engine is advancing rapidly and most likely will soon enter the lower weight classes of 1700 - 2700 lb. According to the present state of the art, it still is a question whether the propeller engine is to be preferred or whether the jet engine will finally prevail. This particular question can be decided only by new developments, adapted to the requirements of touring aviation. In any case, it is permissible to state that the future of aircraft engines of the perform- /4
ance range in question no longer will be characterized by a dominating position of piston engines.

2. Performance Status of Piston Engines

The prospects of piston engines can be evaluated by starting from the

TABLE 1

AVERAGE WEIGHTS AND CHARACTERISTICS OF SINGLE- AND TWIN-ENGINE SPORTS, TOURING, AND BUSINESS AIRCRAFT WITH PISTON ENGINES
Characteristic Weight Classes: 3500, 2500, and 1500 lb

	Twin-Engine Aircraft		Single-Engine Aircraft
Takeoff weight G_A (kp)	3500	2500	1500
Maximum flying speed v_{max} (km/hr)	380	320	280
Takeoff power per engine (hp)	350	260	260
Mean specific weight (kp/hp)	0.67	0.77	0.85
Mean airframe weight G_Z (kp)	1630	1180	580
Mean weight of the power plant G_T (kp)	520	400	240
Mean all-up weight G_R (kp)	2150	1580	820
Payload G_N (kp)	650	500	420
Fuel weight G_B (kp)	700	420	260
Ratio $\chi = \frac{G_T + G_B}{G_A}$	0.350	0.328	0.333
Ratio $\frac{G_Z + G_N}{G_A}$	0.650	0.672	0.666
Ratio $\frac{G_N + G_B}{G_A}$	0.386	0.368	0.453
Ratio G_R/G_A	0.614	0.632	0.546
Ratio G_Z/G_A	0.465	0.472	0.387
Ratio G_T/G_A	0.148	0.160	0.160
Ratio G_Z/G_R	0.627	0.582	0.830
Ratio G_N/G_A	0.185	0.20	0.28
Ratio G_B/G_A	0.200	0.168	0.173
L/D ratio at v_{max}	~1/9.5	~1/9.5	~1/8.5

present technical state of the art of business, touring, and sports aircraft in the USA. At a total number of 120,000 such machines, of which 50% are owned by large corporations, the USA naturally has an especially large market. This leads to a highly efficient mass production; in 1964, the yearly output of touring aircraft was about 10,000, of which up to 1350 alone were of a single prototype (Cessna 172).

A closer look at the production figures will yield the survey shown in Fig.2 as to the distribution of the number of aircraft over the various speed classes. In single-engine machines, the speed range near 220 km/hr (economy model) and near 270 km/hr (luxury model) is especially striking. The classes near 340 km/hr and those above 380 km/hr are grouped similarly for twin-engine machines. The percentage of twin-engine prototypes is near 17.3%, where 10% of the total production go to the luxury class with speeds of 400 km/hr and more.

In Fig.3, the total installed engine power of the individual prototypes is plotted against their maximum speed. The prototypes with equal number of seats are connected by a line. With increasing speed, the area of installed engine power increases constantly. Here, absolute size, aerodynamic quality, required takeoff distance, and especially the ceiling are of major importance. Because of the large distances to be covered on the American Continent, cruising altitudes of 4000 m are useful also for regular business aircraft. This led to the development of altitude engines in the power class between 260 and 400 hp. For example, in the single- and twin-engine luxury class, there is an increase in offer of types with pressurized cabin, using engines with turbosuperchargers.

Considering, on the basis of this statistics, the corresponding number /5
of engines manufactured and referring the latter to the various performance classes, the following conditions will be obtained (Fig.4): Here, specifically

the 140 - 160, 180, and 230 - 260 hp classes are in question. The 160-hp class is used almost exclusively in the category of "economic" twin-engine aircraft (Piper Twin Comanche). In the engine class near 250 hp, single- and twin-engines of the luxury class are included about 50:50. Finally, about 5% of the total number of installed engines exceed a power of 400 hp.

It is of interest to define the technical status of the 11,000 engines built in 1964 in the USA alone: Practically, only engines of the opposed-piston type are used. The number of cylinders of this type engine, up to 165 hp, is usually four, but the six-cylinder Continental O-300 engine of 145 hp is also in rather wide use. In the remaining range, only six-cylinder types are built, except for the Lycoming eight-cylinder IO-720 engine of 400 hp.

In addition, there is a great number of injection engines in use. Above 250 hp, prototypes with fuel injection are exclusively used, while below this horsepower (to 160 hp) about 30% of this type are in use.

Supercharged engines are already in use for various twin-engine types. For example, the Cessna Skymaster has 260-hp engines with exhaust turbosupercharger, while several prototypes of the Aero Commander and the Beech Queen-Air have 340- and 380-hp engines with geared superchargers. Other types were added in 1965, such as the Piper Inka with 310-hp engines and the Cessna 411 with 340-hp engines as well as the single-engine 300-hp Mooney Mustang, which all operate with exhaust turbosuperchargers.

Propeller drives are encountered almost exclusively in engine types with geared supercharger. Dry sump lubrication is preferred at powers above 250 hp.

At present, Continental is building cylinder sizes of 0.8, 1.0, 1.5, and 1.4 liter volume, from which the four-cylinder types of 3.5 - 5.7 ltr swept volume and the six-cylinder types of 4.9 - 8.5 ltr in the building-block design

are derived. The Lycoming has cylinder volumes of 1.0, 1.2, 1.3, and 1.5 ltr, which later led to the four-cylinder series with 3.8 - 5.9 ltr, six-cylinder with 7.1 - 8.9, and one eight-cylinder of 11.9 ltr. The compression ratio /6 (respectively, the octane number) of engines without supercharger is 7 - 7.3 (80/87 ON), while the more modern and more powerful types have compression ratios of 8 - 8.5 (91/96 ON) or up to 8.7 (100/130 ON) and the supercharged prototypes, 7.3 - 7.5 (100/130 ON).

Figure 5 shows the presently available piston displacements, plotted as a function of the takeoff power and the swept volume; Fig.6 shows the piston displacements versus the rpm, with the effective mean pressure as parameter.

Here, several new engine types, placed on the market only in 1965, are taken into consideration, such as the 310-hp T10-541 engine with an exhaust turbosupercharger and the 400-hp TIGO-541 with turbosupercharger and propeller drive, both produced by Lycoming. The specific power output of the simple types is between 25 and 30 hp/ltr, while the most recent engines have values up to 35 hp/ltr, with a rotational speed range close to 2600 - 2700 rpm. Accordingly, the effective mean pressures are near 9 - 11 kg/cm^2, and some even go as high as 11.6 kg/cm^2. The high mean pressures and output per unit displacement are obtained by fuel injection, although this process, in other cases, does not always result in a power increase relative to the carburetor. The use of exhaust turbosuperchargers increases the specific power output of the engines, without propeller drive, to as much as 35 hp/ltr at a mean pressure of 12.2 kg/cm^2. For a further increase in specific as well as in absolute power, propeller reduction gearing is used, permitting an increase in rotational speed to 3200 - 3400 rpm. This raises the power of these engines to 40 hp/ltr and of engines with geared supercharger to 43 hp/ltr at a mean effective pressure of

11.4 kg/cm², while the most recent prototype with turbosupercharger (Lycoming TIGO 541) reaches 45 hp/ltr at a mean pressure of 12 kg/cm². Finally, it should be mentioned that the mean piston speeds of engines without reduction gearing range between 9 and 10 m/sec, while those of engines with gearing rise to 9.5 - 12.6 m/sec.

For comparison purposes, the data of the well-known 18-cylinder double-bank radial engine by Curtiss-Wright with three exhaust turbosuperchargers with gearing, as recently used in the Lockheed-Super-Constellation, should be mentioned:

Type 981 EA 1 17

Stroke/Bore	160.3/155.6 mm
Cylinder volume	3.05 ltr
Stroke volume	54.9 ltr
Compression	6.7
Starting power	3400 hp/2900 rpm (3700 hp/2900 rpm with water injection)
Weight	1663 kg
Swept capacity	62.0 (67.5) hp/ltr
Effective mean pressure .	19.2 (20.9) kg/cm²
Piston speed	15.5 m/sec
Weight per horsepower ...	0.49 (0.45) kg/hp

For an overall view, Fig.7 shows the weight per horsepower of the engines, plotted against the absolute power. In the 100-hp class, this value is 0.9 - 1.0 kg/hp and decreases with increasing power until a value of about 0.7 kg/hp is reached above 300 hp or even less. Of considerable interest is the high weight-per-horsepower of the turbosupercharged engines which, however, is

reduced by the higher engine rpm, i.e., by combination with propeller drives.

An analysis of the USA production for the year 1964 yields the following general picture:

1) In the class of light and low-cost single-engine aircraft (up to four seats, fixed landing gear, maximum speed to 230 km/hr, takeoff weight to 1000 lb) four-cylinder engines up to 150 hp are used for which the decisive factors are cost price, minimum servicing, and low maintenance cost.

2) The medium class of single-engine aircraft (up to five seats, retractable landing gear, maximum speed about 320 km/hr, takeoff weight to about 1500 lb) mainly uses six-cylinder engines up to 250 hp, in which high swept capacity and low specific consumption are the main factors. The same is true for the light class of twin-engine aircraft, of which the Piper Twin Comanche is the main representative.

3) The luxury class of single-engine aircraft (up to five seats, maximum /8 speed to 400 km/hr, takeoff weight to 1700 lb) as well as the twin-engine touring aircraft (up to nine seats, maximum speed to 430 km/hr, takeoff weight 4000 lb) uses six- and eight-cylinder engines up to 400 hp power; recently - because of the supply of small turboprop engines on the market - still higher powers are demanded. In addition to as high as possible an altitude performance, the requirements for large swept capacity and frontal power, next to low specific consumption and quiet operation, are in the forefront.

In the preceding portion of this paper, we analyzed the present technical status of American piston engines for business, touring, and sports aircraft. We will now discuss the possible conclusions as to the future development trend and prospects of piston engines.

2.1 Four-Cycle Engines

2.11 Design

There is no doubt that the four-cycle engine in opposed-piston design will also be the dominant type in the future. Its compact structure, which greatly facilitates installation and accessability, as well as its small frontal area, combined with a favorable air-cooling configuration, constitute the basic advantages of this engine within the performance ranges in question here, compared to other engine types. Figure 8 shows the favorable installation conditions obtained by features such as fuel injection and dry sump lubrication, i.e., elimination of carburetor and oil sump. It should be mentioned that the opposed-piston design, in four- and eight-cylinder engines, also has an ideal compensation of mass forces and moments whereas the six-cylinder engine shows slight residual forces and moments.

2.12 Specific Fuel Consumption

The specific consumption of modern aircraft engines has reached values that can hardly be exceeded downward in the foreseeable future. In carburetor engines, these consumptions are about 210 - 220 lb/hp-hr for partial load. By gasoline injection, a value of about 200 lb/hp-hr for full power and about 180 lb/hp-hr for partial load are obtainable. This presupposes compression ratios of 8.7 and fuels of 100/130 octane.

Unless different fuels and basically more favorable and more industrial /9 processes of mixture formation and combustion can be used, a reduction in these consumptions hardly seems possible. It should be mentioned that the specific consumption has not only a direct influence on the takeoff weight but also an indirect effect on the entire structural volume of the aircraft because of the

bulk of the fuel tank, and naturally also on the fuel cost. Therefore, considerable interest lies in a further reduction in consumption, provided that the reliability will not be lowered by this.

2.13 Absolute Power and Swept Volume

As shown in Fig.5, the absolute power of the piston engines in question here tends toward increasing values. Specifically in the luxury and middle class, maximum flying speeds of at least 350 - 400 km/hr are desired at present so as to make business use more attractive. This leads to power requirements of 400 hp and more. In turn, modern touring aircraft will thus reach thrust loads of more than 0.4.

For increasing the power, two measures are basically in question, namely, an increase in swept volume or an increase in piston displacement. Larger piston displacement means either an increase in volume of the individual cylinder or an increase in number of cylinders. Modern piston aircraft engines have cylinder volumes up to 1.5 ltr. This places limits on a further increase, for thermal reasons. Conversely, a further increase in number of cylinders beyond the conventional eight-cylinder types is impossible for cooling reasons, unless the tried and tested, favorable, and industrially well-adapted opposed-piston design were to be abandoned. Rather, a certain increase in cylinder volume for a six-cylinder opposed-piston engine could be expected.

It is of interest to define the possibilities for an increase in swept capacity. Possibly, the simplest structural measure might be to increase the rotational speed. However, in view of efficiency, the propeller speed is restricted to 2600 - 2800 rpm. A further increase in engine speed would thus require installation of a separate propeller drive. It had been shown before

that engine speeds of 3200 - 3400 rpm could be reached in this manner. A further increase is closely limited by difficulties in cooling and by general /10 wear, since the mean piston speed already is almost 13 m/sec.

An increase in cylinder volume is the second possibility for increasing the swept capacity. At present, favorable valve cross sections are obtained by low values of the stroke/bore ratio (0.75 - 0.8). However, a further increase in bore is opposed by the dynamic problems because of the necessary lengthening of the crankshaft.

A changing from the presently used dual-valve design to two separate intake and exit valves would require considerable technical expenditure. Compared to the conventional connecting rod control, overhead camshafts would be required. This increased expenditure seems hardly justified for an opposed-piston aircraft engine. Similar restrictions are placed on the selection of the compression ratio. Values higher than about 8.7 are inadvisable in view of the knock tendency when using 100/130 octane aviation fuel.

Supercharging represents an especially effective means for increasing the cylinder volume. In modern aircraft construction, superchargers are used either in the form of geared superchargers or of exhaust turbosuperchargers, mainly for improving the altitude performance in view of the fact that, in the luxury class of touring aircraft, the installation of pressurized cabins has created the possibility of cruising altitudes of 4000 m. An increase in sea-level power is obtained only to a limited extent because of the thermal problems involved. For example, the mean effective pressures in modern aircraft engines with exhaust turbosuperchargers are about 12.5 kg/cm^2 as upper limiting value for standard 100/130 octane fuels, whereas engines without superchargers reach a value of approximately 10.5 and, with fuel injection, of about 11.5 kg/cm^2.

The swept capacity of ungeared engines is 27 - 31 hp/ltr at present (with injection, up to 35 hp/ltr), while the values with propeller drive are 35 - 38 hp/ltr and up to 40 hp/ltr with injection; supercharged engines have values close to 34 - 35 hp/ltr and, with propeller drives, up to 40 - 45 hp/ltr. It is highly probable that, in the next few years, swept capacities up to 50 hp/ltr will become possible in the performance class of 300 - 450 hp.

2.14 Frontal Drag /11

The desired high cruising speeds of modern touring aircraft make the "aerodynamic" behavior of the aircraft engine especially important. Not only the frontal area and the installed configuration must be adapted as closely as possible to the aerodynamic form of the aircraft, but momentum losses of the air used for driving and cooling must be reduced as far as possible.

It had been mentioned before that the design of an opposed-piston engine permits an aerodynamically favorable installation. On change-over to fuel injection and dry sump lubrication the engine nacelle can be laid out for minimum frontal drag and can be "tailor-made" also for a twin-engine aircraft. In high-speed cruising flight (350 km/hr), the drag of the aircraft is about 10% of the lift. In this case, the engine nacelles of a twin-engine aircraft contribute about 10% to the total drag. It can be concluded from this that a reduction in frontal area of the engine installation - seen relatively - has the same favorable effect on the flight performance as a percentagewise equally large weight reduction of the power plant. Under consideration of the momentum losses of the air passing through the engine, the engine drag increases to about 20% of the total drag. Here, the throughput of a piston engine is negligibly small with respect to its high cooling-air throughput which is about 20 times as high.

This clearly indicates the great importance of an optimum cooling-air cycle for high-speed touring aircraft. Such a cycle is just as important as the most effective means for increasing the specific engine power. The difficult problem of recovery of the intake momentum will not be treated here.

2.15 Weight per Horsepower

Figure 7 shows the weight per horsepower of modern aircraft engines. In the high-power class above 250 hp, the following values are reached:

Carburetor engine	0.72 kg/hp
Injection engine	0.69 kg/hp
Geared carburetor engine	0.67 kg/hp
Geared injection engine	0.66 kg/hp
Geared injection engine with geared supercharger	0.64 kg/hp
Injection engine with turbosupercharger	0.84 kg/hp

This list clearly indicates that no major reductions in the weight per /12 horsepower can be obtained either by injection or propeller drives or supercharging. Logically, a considerable mutual shift in these values takes place if the data are based on sea-level instead of altitude performance, so that for cruising speeds of 3000 m and beyond, a supercharged engine will show a more favorable weight per horsepower. A certain decrease in this ratio may lead in the near future to an increase in swept capacity, especially by further increase in rotational speed. A direct reduction in weight by structural or material measures can be expected to only a negligible extent. For example, light-metal cylinders did not come into use because of the inadequate barrel properties in the case of large cylinders. In all, the weight per horsepower of modern piston

aircraft engines presumably will not reach or drop below 0.6 kg/hp within the next few years.

2.16 Manufacture and Purchase Price

The sales price of an aircraft engine is of great importance for its selection in the low-power class. Large-scale manufacture permits an especially rational production. Technical peak values, for example, with respect to specific power, will not be absolutely required. However, these requirements are predominant in the medium engine class and especially in the large class of 350 - 400 hp. On the other hand, the sales price also plays a certain role here. This price must be at a reasonable ratio to the overall price of the aircraft which means that, even at high performance, the technical expenditure for the engine cannot be driven arbitrarily high. For example, the cost percentage of the engine is about 20% for a single-engine aircraft and 15% for a twin-engine aircraft. The building-block principle of the opposed-piston engine, used presently by Continental as well as by Lycoming, permits an extensive rationalization of the manufacture since the engines, produced in relatively low numbers and having a larger number of cylinders as well as higher power, profit from the production facilities of the smaller engines that are produced on an assembly line. Thus, rational methods have led to a wide-range delivery program that meets all demands of the aircraft industry, starting from the low-cost 100-hp four-cylinder to the supercharged 400-hp six-cylinder engine. For this reason, except for the high development cost, it is quite improbable that other /13
designs will become popular for such four-cycle piston aircraft engines within the next few years. The present prices of modern aircraft engines are approximately as follows:

for carburetor engines	65 - 69 DM/hp*
for injection engines	75 - 82 DM/hp
for carburetor engines with gearing	98 - 102 DM/hp
for injection engines with gearing	about 116 DM/hp
for injection engines with gearing and supercharger	about 127 DM/hp.

Or, expressed differently, the engine, compared to the basic design with carburetor, will increase in cost as follows:

with injection	by about 18%
with propeller drive	by about 50%
with gearing and injection	by about 74%
with gearing, supercharger, and injection	by about 90%.

In the USA, the share in the total cost, within the aircraft classes in question, was as follows:

engine with carburetor	63%
engine with injection	32.5%
engine with gearing	0.5%
engine with gearing and supercharger	4%.

2.17 Servicing and Operation

The technical conception of an aircraft engine must primarily meet the requirements for reliability. For this particular reason - in addition to weight advantages - air cooling has become popular for all engine types of tour-

* DM = Deutsche Mark.

ing aircraft. However, the thermal stressability of such engines is subject to definite limits which already are almost reached at present.

For any aircraft engine, operational reliability is a basic requisite but operational economy must be maintained nevertheless. The complexity of the structure - due to the trend toward maximum specific performance - must be matched to the available complement of personnel and equipment. No doubt, in regular commercial airlines this is satisfied to the largest possible extent, but for private aircraft and small airfields this is actually undesirable. For this reason, the servicing requirements of a given aircraft engine must be evaluated from the viewpoint of economy as well as reliability. /14

A criterion for evaluating the cost efficiency of a modern aircraft engine is represented by the officially prescribed operating period before general overhaul. At present, the average periods are as follows:

for carburetor engines	1200 hrs
for injection engines	1000 hrs
for geared engines	1000 hrs
for injection engines with gearing	900 hrs
for injection engines with supercharger and gearing	900 hrs.

2.2 Two-Cycle Engine and Rotary Engine

The above statements referred almost exclusively to the four-cycle engine which is in general use at present in performance classes above 100 hp. In our opinion, it is highly improbable that the two-cycle engine will ever be introduced as an aircraft engine for such output. Primarily, the much greater fuel consumption and the greater cooling requirements exclude this possibility.

Conversely, the two-cycle engine seems more advantageous than the four-cycle engine in the performance class below 100 hp, specifically below 50 hp, because of cheaper construction, higher specific power output, smaller bulk, and lower weight per horsepower of the progressive recent developments. The weight advantage, compared to a four-cycle engine, is canceled already after one hour of flying. For this reason, the technical solution of a simple and low-cost injection device is of considerable importance for the future prospects of two-cycle engines. At present, small four-cylinder two-cycle aircraft engines in opposed-piston construction of 26 - 48 hp can be delivered (Hirth, Nelson), yielding swept capacities of up to 48 hp/ltr and weights per horsepower of 0.95 kg/hp. The weight of the reduction gearing is of special importance in small engines. For short-time use, high-power two-cycle engines with supercharging by Roots blowers and exhaust turbosuperchargers were developed. As six-cylinder opposed-piston designs (McCulloch) or as four-cylinder radial /15 types (Meteor), these engines furnish 120 - 160 hp at 45 - 60 hp/ltr and rotational speeds of 3000 - 4000 rpm. Without gearing, the engines give weights per horsepower of 0.8 - 0.5 kg/hp. In the latter case, a double-bank radial design will lead to a doubling of the output at equal swept capacity and weight per horsepower of 0.6 - 0.4 kg/hp.

From such special engines it might well be possible to derive modern, light, cheap, and serviceable small aircraft engines which, in turn, would greatly promote the construction of modern and low-cost light aircraft. The main condition for progress in the use of two-cycle engines seems to be a satisfactory solution of the cooling problem in continuous operation.

Finally, the prospects of rotary engines based on the NSU* Wankel principle

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* NSU = NSU Werke A.G.Neckarsulm (licensees of "Wankel motor").

as aircraft engine for touring aircraft should be mentioned. The use of this prototype is favored specifically by the short length and small frontal area. In establishing the weight balance, the propeller drive must always be taken into consideration. Presumably, this thermally highly stressed engine will require water cooling, whose weight and susceptibility to failure are by no means desirable. The development, started more than eight years ago at the NSU, does not yet permit an estimate as to the possible prospects of this engine for the purpose in question here.

Specifically, an evaluation of the wear behavior, servicing conditions, and operational reliability will be required.

2.3 Evaluation of the Development

The development trend of the American single- and twin-engine touring aircraft points toward cruising speeds of more than 400 km/hr at average altitudes of 4000 m. Also in Europe, business and private touring aircraft, under the effect of the incipient European integration, will increasingly follow this direction. The requirements as to horsepower of 350 - 400 hp and more for the aircraft engine and the necessity of supercharging are results of this. These engines most likely will be the most modern modifications of piston engines, after turboprop engines have penetrated the performance class near 500 hp. The conventional design as six-cylinder and eight-cylinder opposed-piston engines operating on the four-cycle principle will most likely be retained within the foreseeable future, since this design is especially favorable with respect to structure, drag, and cooling.

In view of the fact that the piston aircraft engine has already reached /16 an advanced state of development, no major changes of its characteristics com-

pared to present American high-performance engines of the 350 - 400 hp class can be expected. Piston displacements of 50 - 55 hp/ltr, at piston speeds of 13.5-14 m/sec and effective mean pressures close to 12.5 kg/cm^2 (supercharged), seem entirely possible. As six-cylinder engine with ten-liter stroke volume, a power of 500 - 550 hp at a weight per horsepower of close to 0.6 kg/hp can be expected. For comparison, we are giving the energy balance of a typical touring aircraft:

> 10% savings in power/weight ratio of the piston engine are approximately equivalent to 10% savings in specific fuel consumption for a three-hour flight.
>
> 10% savings in engine power/weight ratio are approximately equal to 10% savings in drag of the engine nacelle during high-speed flight (400 km/hr).

It is left to the future to decide in how far such a progressive engine will prevent further penetration of turboprop engines into the lower performance range. Including fuel consumption, this will not be more favorable than the prop-jet engine, even at a flying time of four hours. No doubt, the aerodynamic drag of the piston engine, specifically under consideration of the greater air-cooling requirements, will be higher. The structural expenditure and the manufacturing cost will not differ much from the prop-jet engine, taking into consideration injection, gearing, supercharger, and control elements.

The structural and technical characteristics of such a piston aircraft engine will have an effect on aircraft engines of lower power. No doubt, fuel injection will become more popular. In addition to a fuel saving of about 10% at approximately equal power gain, the decrease in frontal drag and the prevention of possible icing are of great advantage. Especially if a simple in-

jection device should be found, excellent chances exist for the two-cycle engine in the power range below 100 hp. However, this presupposes that the cooling problems for continuous operation can be solved.

3. Performance Status of Turbine Engines, Specifically Turbojet Engines /17

The present availability of small turbine power plants permits the statement that no turbine engine exists in the lower performance classes that could be considered a true replacement for the piston engine which, at present, is used as standard equipment for light aircraft of the above-defined weight classes between 1500 and 3500 lb. The presently existing single-flow jet engines are so designed and dimensioned that they require an airframe designed for cruising speeds above 700 km/hr and cruising altitudes of more than 7 km, whose price level is entirely different from that of piston-driven aircraft of the above weight classes. Beyond this, as a consequence of considerably higher wing loading, the takeoff distances have increased to twice and three times the original value, whereas the payload components have dropped by almost half in some cases. It is true that the modern dual-flow engines yield higher takeoff thrust and permit takeoff distances of less than 700 m, but these engines because of their specific design require much higher cruising speeds and thus more elaborate and more expensive airframes. A better comparison is given by propeller-driven turbine aircraft despite the fact that the presently available and economically bearable turboprops, of 600 - 700 hp, are still too powerful. A consequence of this overdimensioning is an above-average shortness of takeoff distances and unusual cruising speeds of such propeller aircraft which, naturally, appeal to the customer and thus prescribe certain power requirements from the beginning.

This obviously means that there is a lack of suitable jet engines, useful for cruising speeds of 500 - 550 km/hr and a cruising altitude of about 4 km. It should be possible to develop an airframe for such a propulsion system, whose costs would be comparable to the piston aircraft, which would automatically bypass the heavier turboprop engine which requires much more servicing. Naturally, this still disregards the purchase price of the propulsive unit, but such a jet engine will be much cheaper than a turboprop engine, at comparable performance. However, the total expenditure, expressed by the takeoff weight, should remain the same, at acceptable range and payload components.

The total expenditure as well as the range and payload component, however, depend largely on the specific fuel consumption and on the thrust-specific /18 engine weight. In turn, these characteristics are decisive for the layout and quality factor of the compressor, turbine, and combustion chamber. In the case of small engines, these structural elements represent a critical point that must be overcome.

Therefore, it can be stated in general that - as shown in Fig.9 - the specific takeoff thrust to fuel consumption will decrease with increasing takeoff thrust, i.e., with absolute size of the power plant, since higher compressor ratios are easier to realize in larger engines and since the increase in weight produced by an increase in compression ratio does not influence the thrust-specific weight to the same extent. It is true that, at a geometric reduction, the power/weight ratio of the rotor is improved but the surface roughness, clearance, and mutual interference of the blades, because of the relatively heavy boundary layer etc., will have a considerable influence in small power plants. Beyond this, any reduction in size of the engines makes the combustion-chamber configuration more important. Despite the fact that, starting from

certain throughputs, the dimensions (and weights) of the combustion chambers become greater than those of the rotors, the combustion-chamber efficiencies - because of the poorer combustion - are ordinarily lower than in large engines since the combustion-chamber length greatly decreases with decreasing engine size.

As shown by the recent development of a shaft engine of 350 hp, compression ratios of 7.5 are still possible for small engines, because of a combination of radial compressors with axial compressor stages. From the fluid-dynamics viewpoint, this yields considerable alleviations and produces acceptable compressor efficiencies of the order of 83 - 86%. Thus, in the engine family J69, a simple radial compressor engine of 400 kg takeoff thrust resulted in a progressive power plant by addition of axial stages; however, this engine was rated for a 2.5 fold thrust but showed an above-average thrust weight, close to the characteristics of the light engines J85 and RB145, as well as a considerably /19 reduced fuel consumption. On the other hand, this indicates that an increase in size yields advantages in every direction. Figure 9 also shows the effect of the dual-flow principle on the specific consumption, with a clear gradation according to the bypass ratio, together with the influence of engine size and compressor ratio.

The statistics in Fig.10 yields data on the influence of size on the thrust-specific engine weight and on the throughput thrust, plotted against the total throughput of the engines. The upper diagram distinctly shows the difference between modern and older power plant types; the latter are characterized by conventional design, i.e., by moderate compressor ratios close to about 4.5, and by moderately high turbine inlet temperatures. Less clear are the conditions in dual-flow engines; here, the influence of the state of develop-

ment is superposed by that of the bypass ratio, characterized by the structural expenditure for the fan including the reduction gearing which might be required for the blower unit.

The throughput thrust or specific thrust also depends on the size; the upper limit is given by the more modern light engines and the lower limit is established by older types. Naturally, the turbine inlet temperature has a considerable influence on the specific fuel consumption, on the throughput thrust, and on the thrust-specific engine weight. The true influence on these properties cannot be determined statistically since too few data are available on this point.

Within comparisons of turboprop engines and piston engines made elsewhere (Bibl.1), several properties of turboprop engines for low powers are given, so that we need only discuss the performance status of such units.

At present, the small turboprop engines on the market cover a power range of 250 - 750 hp, and the number of available prototypes has increased to almost 10 in the meantime.

In turboprop engines, the upper limits are less narrow for the selection /20 of the compressor ratio and thus for the turbine inlet, since gas turbines are used only for energy conversion and not for production of the jet. Thus, the energy gradient, downstream of the compressor turbine, can be utilized fully; consideration of the jet or of the propulsive efficiency is necessary only in dimensioning the propeller. For this reason, turbine inlet temperatures of about 1000°C are encountered in modern small engines (Table 2). Naturally, this temperature must be accompanied by a correspondingly high compression ratio, between 7 and 8, if optimum values for the consumption are desired. This consumption, for a 640-hp engine, is already close to 230 lb/hp-hr (on takeoff);

on the average, the value is 270 - 290 lb/hp-hr for engines of 500 - 600 hp. Nevertheless, a considerable reduction in consumption can be obtained by improving the component efficiencies. For example, an increase in turbine efficiency by 2% will decrease the specific consumption by 4 - 6%. With respect to consumption, turboprop engines cannot yet compete with high-grade piston engines, specifically not in the power range of 250 - 350 hp, although a power plant is in the development stage which is to reach a consumption of 260 lb/hp-hr. However, with respect to the power/weight ratio, the piston engine is totally inferior to the turboprop engine within this particular power class. Values of 0.20 - 0.26 kg/hp are competing with values of 0.65 - 0.86.

The state of development in the upper region of the performance class considered here indicates that turboprop engines will be increasingly successful for touring aircraft, in which case - compared to piston-driven aircraft - the total expenditure, payload component, and range can be kept at approximately equal values. However, the takeoff power of 600 - 700 hp per power plant is approximately twice as high as in piston aircraft which, as mentioned before, leads to above-average flight performance. Conversely, the turboprop engine has not yet been used in the lower power range for touring aircraft, except in small military helicopters, since the present performance status still means excessive deductions of payload and range. Beyond this, the manufacturing and maintenance costs of these engines are in no reasonable ratio to the expenditure and cost of the aircraft classes in question for engines of this size. The /21
maintenance cost is determined by the overhaul periods which, for example in the PT6 engine, are 800 hrs at present and thus are still below those for piston engines.

The geometric reduction in size of turboprop engines is even more difficult

than that of jet engines, because of the reduced throughput; in addition, such a reduction in size has to do with the fact that weight and structural volume of reduction gearing, propeller-pitch change and control mechanisms soon will reach those of actual gas turbines and, for the smallest engines, even will exceed these. Consequently, a geometric reduction in size is characterized not only by the attempts at optimum component efficiencies but also by adaptation to the construction of progressive auxiliary equipment, since it is not of much use to equip a modern power plant with auxiliary devices that had been designed along conventional principles with respect to weight and structural volume. So far as the structural volume is concerned, certain limits will be encountered downward beyond which a further decrease in size of gearing, auxiliary drives, and similar devices is no longer possible.

In summation, it can be stated that a decrease in specific takeoff thrust consumption for single-flow engines to values below 0.95 kg/kg-hr cannot be expected in the very near future for the 400 - 600 kg thrust class. A major reduction in consumption is possible only by using ducted-fan engines whose by-pass ratio tends toward 6. With such engines, consumptions close to 0.5 kg/kg-hr could be obtained. With respect to structural weight, an increase in compressor ratio and turbine inlet temperature beyond the present average values of 6.5 resp. 800°C to values of 8 resp. 1000°C might be conceivable since, by structural and material measures, the present thrust weights of 3.0 to 3.5 kg/kg most likely cannot be increased beyond 4.5 kg/kg. In dual-flow engines, a slight amount of development work could lead to an increase in the present thrust weights of 2.5 - 3.0 kg/kg to 4 kg/kg. In turboprop engines, a decrease in power/weight ratio to less than 0.18 kg/hp is practically out of the question; however, an improvement in consumption to values between 200 and 230 kg/hp-hr

TABLE 2

CHARACTERISTICS OF TURBOPROP ENGINES UP TO 700 hp TAKEOFF POWER

Prototype	Takeoff Power (Brake Horsepower) hp	Specific Fuel Consumption lb/hp-hr	Power/Weight Ratio kg-hp	Compression Ratio –	Turbine Inlet Temperature °C	Air Throughput kg/sec	Turbine rpm of the Power Turbine rpm
Turboméca Astazou 10	640	230	0.200	7.5		2.8	43,000
Airesearch TPE-331	600	281	0.203	7.9	943	2.5	41,750
Pratt & Whitney PT6A-6	550	294	0.222	6.3		2.4	33,000
Turboméca Astazou 2	530	272	0.232	6.0		2.5	43,300
Turboméca Orédon 3	350	259	0.233	7.5			
Allison 250-B15	310	308	0.225	6.2	985	1.4	35,000
Allison 250-B1	250	322	0.268	6.2	871	1.4	48,750

is well within the range of possibilities since, in selecting the compressor ratio and turbine inlet temperature, slightly greater tolerances are permissible. The improvement in component efficiency, however, is the most decisive factor here. Whereas the turbine engine has possibilities for improvement in specific consumption and thrust weight, comparable manufacturing costs for piston engines can be obtained only by large-scale production which would lower the present

manufacturing cost of 150 - 170 DM/hp. Conversely, the expenditure for servicing can be considered more optimistically, when thinking of a parallel to large engines. In addition, considerable improvement has been made in this respect in recent times.

4. Design of Supercharged Engines for Light Aircraft /23

At the beginning of this paper, we talked of replacing the piston engine in light aircraft of the 1500 - 3500 lb class by a still to be developed turbine engine; in this connection, the suitability of supercharged engines was considered a possibility. This is a postulate which now will have to be substantiated by actual calculation.

This necessitates two basic requirements made on power plants with respect to their design and dimensioning and resulting from the specifications for the aircraft classes in question: first, the requirement for a sufficiently high takeoff thrust, expressed by the thrust loading as the ratio of takeoff thrust to takeoff weight of the aircraft, and secondly the requirement for a tolerable specific fuel consumption in cruising, provided that the specific engine weight has acceptable values.

Conversely, the absolute engine weight is decisively determined by the magnitude of thrust loading. In turn, thrust loading results either from the requirement for takeoff distance or, as demonstrated below, from the cruising conditions, if the altitude or speed behavior of the engine is such that the required cruising thrust can be used as basis. As a rule, the required thrust loading is obtained from the takeoff conditions: To be able to offer a progressive aircraft on the market, the takeoff distances of 300 - 350 m of several more recent turboprop aircraft of the 3500 and 2500 lb class must be used in the

calculations, if as many as possible of the available seats are to be used (Fig.11). Under assumption of average coefficients of lift C_{L2} of about 1.75 - 1.85, this will lead to thrust loadings of 0.30 - 0.35, assuming that, in view of cruising speeds of presumably 500 - 550 km/hr, wing loadings of 150 - 180 kg/m^2 are desirable. The cruising speed to be selected depends primarily on the requirement of range and on the consumption behavior of the still to be designed power plant (Bibl.5).

Assuming a certain percentual share in the takeoff weight for the pure airframe weight and, beyond this, defining the payload share, the permissible percentage for engine and fuel weight, known as percentual propulsive weight, /24 is automatically defined. The requirements for range can be described with sufficient accuracy by Brequet's range formula. On correlating this formula with the value for the percentual propulsive weight and with the definition equation for thrust loading (Fig.12), a relation will be obtained between flying time R/v_0, specific fuel consumption in cruising b, thrust weight of the engines p as the ratio of takeoff thrust of the engine to its installed weight, and the thrust loading which, together with the thrust weight, is representative for the absolute engine weight. The diagram thus shows the requirements to be made on the power plant systems of light jet aircraft. Assuming furthermore that, for these aircraft, a cruising L/D ratio of 1/9.5 can be realized and basing the percentual propulsive weight, in analogy to the statistically obtained average values of modern light piston aircraft allowing for an increase in absolute airframe weight on increase in overall speed, on a numerical value of $\chi = 0.34$, then the specific fuel consumption in cruising can be 0.9 kg/kg-hr if, for example, a cruising time of three hours is required, if a thrust loading of 0.3 is necessary, and if an installed thrust weight of the engine of about 3 kg/kg

takeoff thrust can be realized. At a cruising speed of 550 km/hr, this means a range of 1650 km; however, this yields no data on the absolute expenditure, expressed by the final takeoff weight.

Before making statements on this point, the overall design of the engine must be accurately defined. For example, this could be a ducted-fan engine which, in view of the cruising speed to be selected, would have an above-average bypass ratio. For the basic engine of such a blower-type propulsive system, in analogy to existing small engines, a compressor ratio Π of 6 should be selected and a turbine inlet temperature T_3 of 1300°K. Whereas the selected compressor ratio is easy to realize in small engines at present and already furnishes acceptable thermal efficiencies, the turbine inlet temperature seems too optimistic and not quite accurate. Nevertheless, according to the present or future state of the art in materials technology, such turbine inlet temperatures /25
without blade cooling will be possible in continuous operation. This temperature which, incidentally, is slightly above the optimum value corresponding to the compressor ratio, will lead to a correspondingly higher fuel consumption because of the somewhat too high exit velocity. However, in a dual-flow engine with a high bypass ratio, a slightly greater tolerance is available in selecting the combustion-chamber end temperature, which can be utilized in so far as the basic engine, because of the now possible higher energy yield per kilogram air throughput, can be made smaller and lighter in weight. Thus, in turbojet engines, an increase in turbine inlet temperature from 800° to 1000°C will lead to an improvement in the thrust weight by 15 to 20% (Bibl.6).

The specific fuel consumption is also influenced greatly by the efficiency of turbine, compressor, and combustion chamber. A precalculation of engine characteristics thus has some uncertainties since these efficiencies can be

estimated only on the basis of available designs. However, we believe that turbine and compressor efficiencies of 83% closely approach the real conditions. One could object that an assumption of a combustion chamber efficiency of 90% is somewhat too pessimistic; however, it must be remembered that combustion chambers under high load will be used in general which, because of smaller structural dimensions, have poorer combustion degrees than combustion chambers of large engines. In any case, the values conventional for large engines, of 0.96 - 0.98, cannot be used as basis for small engines (Bibl.7).

Under consideration of the above assumptions and statements, Fig.13 shows the optimum bypass ratio z_{opt} as a function of the cruising Mach number M_0. This is the bypass ratio at which the thrust, referred to the primary throughput, becomes optimum. Obviously, in selecting a turbine inlet temperature of 1300°K at a cruising Mach number of 0.45 and a cruising altitude of 4 km, a bypass ratio of about 6 will be required (Bibl.8).

Here, we should introduce a statement on the cruising altitude. For touring aircraft which, in the majority of flights, cover only relatively short distances, it is not necessary and also not advisable to extend the cruising altitude, for which the engine is to work at optimum conditions, much beyond 4 km, specifically since only a moderate increase in cruising speed beyond that of piston aircraft is attempted. Therefore, a cruising Mach number of 0.45 and an altitude of 4 km are considered adequate guidelines. The higher the cruising Mach number, the higher will be the required wing loadings and the more difficult will it be to satisfy the takeoff distance requirements. /26

Another problem is that of the optimum bypass/compression ratio Πz_{opt}. Figure 14 shows the correlation between Πz_{opt} and the cruising Mach number, obtained from an optimization of the specific throughput thrust. Thus, for M_0 =

= 0.45 a bypass/compression ratio of about 1.3 should be selected. The superposition of the two latter plottings is shown in Fig.15, which gives the coordination of flight Mach number, bypass ratio, and bypass/compression ratio. In agreement with an American engine development, a bypass ratio of about 6 and a bypass/compression ratio of about 1.3 can be selected for a cruising Mach number of $M_0 = 0.45$. This graph and the preceding diagram are based on a nozzle efficiency of 0.95 and an intake efficiency of more than 0.9. In all other respects, the results listed here, and still to be listed, are valid for an unmixed exhaust of primary and secondary air.

Another diagram (Fig.16) shows the thrust relative to the primary throughput, the specific thrust S^*, as a function of the bypass ratio. This diagram indicates the considerable thrust gain obtainable with respect to a single-flow engine when using a fan drive with comparable primary throughput; the plot also shows the altitude speed behavior of the ducted-fan engine compared to a single-flow engine, which manifests itself in a thrust decrement by almost double the sea-level thrust using a bypass ratio of 6 and a cruising Mach number of 0.45 as basis.

This must be taken into consideration in connection with takeoff thrust /27 requirements in dimensioning the power plant. Whereas, in single-flow engines and dual-flow engines, with bypass ratios up to about 2, the requirements for takeoff distance are decisive for the sizing and thus a sufficient thrust is usually available for cruising, the use of fan-type engines with bypass ratios above 2 might lead to the possibility that the required thrust in cruising becomes decisive for the engine size so that the takeoff requirements are met automatically. In the former case, a slight throttling is necessary to maintain certain cruising conditions, whereas the thrust behavior of a fan-type

engine may permit matching of takeoff and cruising conditions, so that the takeoff and cruising requirements will coincide with the thrust behavior of the engine. In this connection, it can be stated in general that, the higher the aerodynamic quality of an aircraft in cruising the more decisive will the takeoff conditions become for the engine dimensioning.

Figure 17 shows the gain in thrust, expressed here by the thrust ratio F_z/F_0 obtainable - with respect to a single-flow engine - by proper utilization of the available energy and under consideration of the selected bypass ratios. This indicates that, at given takeoff or cruising conditions, the use of the dual flow principle will require a much smaller basic power plant. However, this thrust augmentation - in the case of smaller power plants - may be accompanied by a minor impairment in thrust weight since the dual-flow engine has a higher specific weight because of the blower used; nevertheless, the decrease in specific fuel consumption is a sensitive factor and of considerable importance.

Figure 18 gives the specific fuel consumption as a function of the bypass ratio and the flight Mach number. It is admitted that the consumptions, determined here, are too pessimistic. However, this is exclusively due to the fixing of the partial efficiencies, especially that of the combustion chamber efficiency, and only negligibly to the selection of the turbine inlet temperature. The plotted values of several single- and dual-flow engines with at least comparable compressor ratios indicate that the consumption can be set by 10 - 15% less. However, as will be discussed later, the drag of the engine /28 must also be considered, meaning that a net fuel consumption is used in the calculation after deducting the engine drag from the produced engine thrust. In general, it seems quite obvious that it is useless to increase the cruising

Mach number to much more than 0.45, since ducted-fan engines with bypass ratios above 3 already show consumptions too high for economic use.

In Fig.19, the available results are compiled in a characteristic field. This field thus applies to an altitude of H = 4 km and is based on the engine thrust referred to the total throughput. The diagram again shows the necessity for large bypass ratios if the flights are to take place at moderate cruising speeds. The dependence of the engine thrust (relative to the total throughput) on the bypass ratio, plotted in Fig.20, indicates the above-mentioned weaknesses of a dual-flow engine, namely, the greater frontal area compared to single-flow engines; this is due to the fact that, at increasing bypass ratios, ever larger air masses will be put through and accelerated to exhaust velocities which constantly decrease with increasing bypass ratios. Consequently, if dual-flow engines are developed from single-flow engines by adding a blower stage, the resultant thrust augmentation will be accompanied by an inordinately high diameter increase. Therefore, relating the blower diameters D_s to the diameters of the corresponding basic power plant D_P, Fig.21 will give the dependence of this ratio on the bypass ratio, plotted in the curve a. The values of full-scale devices agree well with those of the theoretically determined curve of the superimposed arithmetic law based on the assumption that primary and secondary stream, with a common mean intake velocity and independent of the bypass ratio, are able to flow through the intake plane of a reference intake sufficiently far from the engine and having a diameter representative for the blower diameter. Conversely, if thrust equality is used as the reference basis, a much more favorable picture will be obtained for the dual-flow engine, as shown by the statistically obtained curve b; however, this comparison is not completely objective since, on the basis of the thrust behavior of the fan

drives, changed with respect to the single-flow engine, a characteristic cruising state rather than takeoff thrust (as done here and in Curve a) would have to be selected as comparison basis. Nevertheless, in a ducted-fan engine with /29 a bypass ratio of 6, approximately a 1.6 fold frontal diameter must be expected, a disadvantage which also manifests itself in the frontal thrust q_v. Here, q_v is the ratio of takeoff thrust to frontal area of the engine. Using the above-defined reference intake with its respective conditions as basis, a hyperbolic dependence of the frontal thrust on the bypass ratio is obtained in first approximation in agreement with the slope of the specific thrust in the preceding diagram; this represents a correlation which indicates that, in the region of high bypass ratios (for example, above 3) the influence of this ratio on the frontal area requirement decreases. This is more or less confirmed by the statistics in Fig.22. Accordingly, the frontal thrusts first decrease strongly with the bypass ratio in the region of the upper thrust classes and then show a less strict dependence on the bypass ratio in the region of lower thrust. Naturally, only engines of the same thrust class with at least somewhat similar compressor ratios were interconnected here. Nevertheless, the increase in frontal area compared to single-flow engines can no longer be neglected in designing jet engines with compressor drives. To obtain an objective comparison with single-flow engines, the net thrust remaining after deduction of the engine drag must be referred to the fuel consumption per hour of the engine, and the resultant net consumption must be used as basis for all further calculations. However, a determination of the engine drag is dependent on a suitable assumption of the coefficient of drag.

A diagram (Fig.23) published by Lycoming gives a general survey over the influence of the engine drag on the specific consumption but for different

engine design data, such as a compressor ratio of 10, a bypass/compression ratio of 1.4, a turbine inlet temperature of 1225°K, and a flight Mach number of 0.6. Nevertheless, the diagram gives the order of magnitude by which the consumption must be raised if the engine drag of the engines suspended in pods below the wing is to be taken into consideration. Within the range of the bypass ratios in question here, an increase in consumption by 10 - 15% must be allowed for, which will shift the optimum bypass ratio toward lower values. Thus, the consumption data shown in Fig.18 closely approach existing conditions (Bibl.9). /30

The above results of calculating a fan-type engine for high bypass ratios near 6, to be used as propulsive unit for higher-class sports, cruising, and business aircraft with takeoff weights of 1500 - 3500 lb, indicate that the required maximum and minimum values of various specific characteristics, mainly of the specific cruising fuel consumption and the thrust-specific engine weight, can be met if a characteristic cruising speed of 520 - 550 km/hr is demanded for a cruising height of 4 km, if the flying time is not more than three hours and if a takeoff distance of 300 - 400 m is not to be exceeded.

In view of this, the specific cruising consumption may have a maximum of 0.9 kg/kg-hr and a takeoff thrust of 3 kg/kg for the specific engine weight. Both values presumably are obtainable at the present state of engine design. If these values are used as basis, a range requirement of 1650 km and a takeoff distance of 300 m will lead to an aircraft with two power plants of 500 - 600 kg takeoff thrust each and, depending on the altitude cruising consumption (0.8 - 1.0 kg/kg-hr) to a takeoff weight of 3600 - 4200 lb.

Thus, compared to a comparable aircraft with piston drive, an increase in total expenditure up to 15% can still be tolerated, although the payload com-

ponent of the takeoff weight has remained at 20% and the cruising speed has been increased on the average from 350 to 520 km/hr. Compared to turboprop aircraft, this eliminates the need for a propeller-pitch change system which requires excessive maintenance, although the blower of a two-cycle engine will need a reducing gear which, no doubt, will render it difficult to maintain a thrust of 3 kg/kg. For sea-level conditions and for a bypass ratio of 6, a primary throughput of 3.4 - 4.0 kg/sec and a secondary throughput of 20 - 24 kg/sec are obtained. For a final determination of the bypass ratio, the accurate determination of the additional drag must be supplemented by the increased airframe weight, produced by the presence of the blower. Finally, an optimizing of power plant weight and fuel consumption must decide the final dimensioning of /31 compressor ratio and turbine inlet temperature, with consideration of the manufacturing costs.

5. Final Remarks

The purpose of this paper was to present a brief outline of the present performance status of piston engines and turbine engines used in the lower performance range, and to follow this by a discussion of turbojet engines with a blower drive and extremely high bypass ratios, which would make it possible to replace the piston engine as well as the turboprop engine in certain light aircraft classes by true jet propulsion systems. Therefore, the discussions mainly centered on the design and size determination of such propulsive drives, for whose final evaluation of suitability a more accurate and detailed analysis is naturally required. Specifically, items such as overhaul periods, correlated maintenance costs, etc. must be included in the calculations.

There is no doubt that the design of such a power plant will require de-

velopment work over a period of years and that this type of engine has three main drawbacks which can be eliminated only in part, namely:

1) To obtain cruising times of four hours, the specific fuel consumption must be decreased to below 0.85 kg/kg-hr and the thrust weight must be increased to 4 kg/kg takeoff thrust. These improvements are definitely in the range of possibilities, since the component efficiencies were rather pessimistically evaluated despite the fact that the thermal efficiency cannot be increased by much.

2) The noise generation is a more difficult problem since, with the present means, it cannot be eliminated or even partly overcome. The jet noise can be reduced somewhat by increasing the bypass ratio but this will lead to more high-frequency noise produced by the blower itself. Here, an optimum is obtained at bypass ratios which, for the desired flying speed, are far below the consumption-optimum bypass ratio.

3) The problem of manufacturing cost is critical but not completely un- /32 solvable; however, this cost is not far from the comparable piston engines with gasoline engine and exhaust turbosupercharger. The decrease in cost could be obtained by developing cost-saving manufacturing methods, but a distinct improvement in the situation is possible only by large-scale production which would then absorb the development cost.

It should also be stated that a power plant of the above-described type will have a more or less strong influence on the airframe design, although a completely unconventional configuration will not be necessary. Certain installation difficulties might occur in single-engine aircraft leading to preferential use of turboprop engines which are available for this type of aircraft.

The question of cost efficiency no doubt may lead to the creation of a type

of standard engine which would exist in only a few variants and could be used for a large number of aircraft prototypes. It might well be that an international consortium of firms experienced in the construction of small engines might take over such a development. A step of this type would offer promising prospects for turbine engines in the field of light aircraft; however, this would not automatically pass the death sentence on the piston engine since this type of engine cannot be replaced for very small aircraft.

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Sump, Compared to an Engine with Injection and Dry Sump.

Fig.9: Specific Fuel Consumption as a Function of the Absolute Thrust and the Compressor Ratio for Full-Scale Single- and Dual-Flow Turbojet Engines of the Lower Thrust Class. According to Wilkinson (Bibl.4).

Fig.10: Thrust Weight and Specific Thrust (Throughput Thrust) as a Function of the Total Throughput, for Full-Scale Single- and Dual-Flow Turbojet Engines of the Lower Thrust Class. According to Wilkinson (Bibl.4).

Fig.11: Required Thrust Loading as a Function of the Wing Loading and the Coefficient of Lift during Takeoff.

Fig.12: Permissible Specific Fuel Consumption in Cruising b as a Function of the Thrust Weight of the Engine System p, for Various Flying Times R/v_0 and Thrust Loadings. Here, χ = percentual propulsive weight, ϵ = optimum cruising L/D.

Fig.13: Optimum Bypass Ratio z_{opt} as a Function of the Cruising Mach Number M_0. Here, Π = compressor ratio, Π_z = bypass/compression ratio, T_3 = = turbine intake temp., T_0 = ambient temp., H = altitude of flight.

Fig.14: Optimum Bypass/Compression Ratio as a Function of the Cruising Mach Number. /35

Fig.15: Coordination of Cruising Mach Number, Optimum Bypass Ratio, and Optimum Bypass/Compression Ratio.

Fig.16: Specific Thrust S^* as a Function of the Bypass Ratio and the Cruising Mach Number.

Fig.17: Possible Thrust Increment by Use of the Dual-Flow Principle, for Π = 6 and $T_3 = 1300^\circ K$.

Fig.18: Specific Consumption in Cruising as a Function of the Bypass Ratio

and the Cruising Mach Number. Curve a refers to statistically determined values of full-scale jet engines.

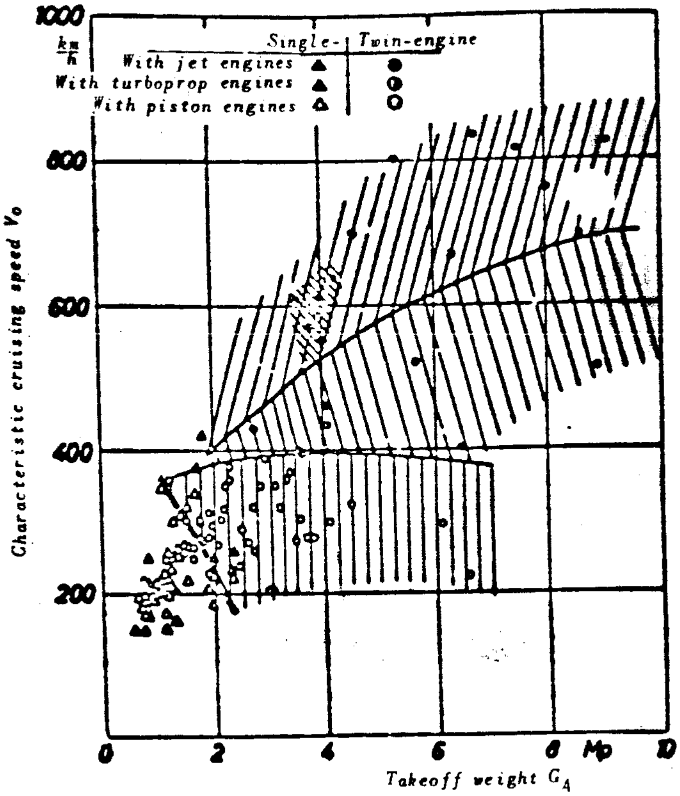
Fig.19: Characteristic Field for Two-Flow Engines of Various Bypass Ratios.

Fig.20: Specific Thrust S as a Function of the Bypass Ratio and the Flight Mach Number.

Fig.21: Frontal Drag and Diameter Ratio as a Function of the Bypass Ratio.

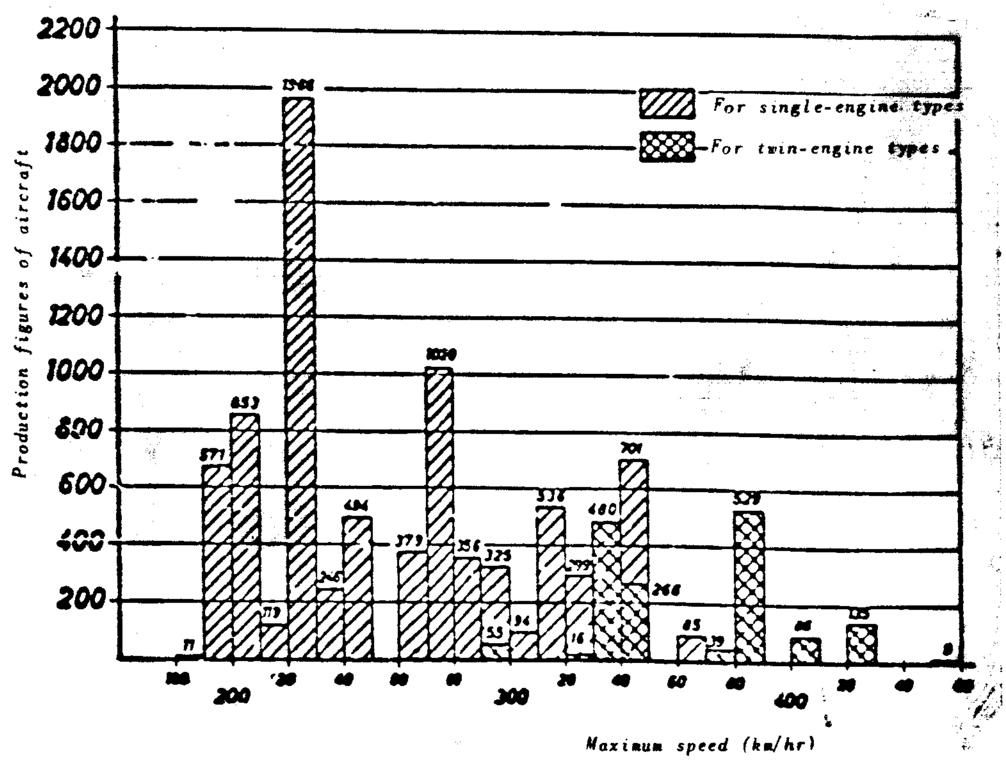
Fig.22: Frontal Thrust of Full-Scale Single- and Dual-Flow Engines, Arranged by Thrust Classes and Compressor Ratios.

Fig.23: Influence of Engine Drag on the Estimated Specific Fuel Consumption of Dual-Flow Engines, according to Lycoming (Bibl.9).



1000
km/h
Single- | Twin-engine
With jet engines
With turboprop engines
With piston engines
800
600
400
200
Characteristic cruising speed V_0
0
2
4
6
8 Mp
10
Takeoff weight G_A

Fig.1



2200
2000
1800
1600
1400
1200
1000
800
600
400
200
Production figures of aircraft
For single-engine types
For twin-engine types
200
300
400
Maximum speed (km/hr)

Fig.2

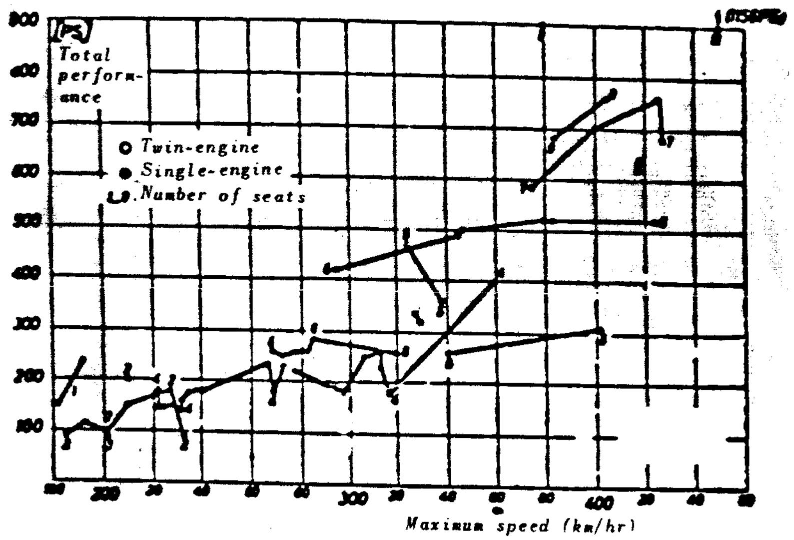

[PS]
Total performance
Twin-engine
Single-engine
Number of seats
Maximum speed (km/hr)

Fig.3

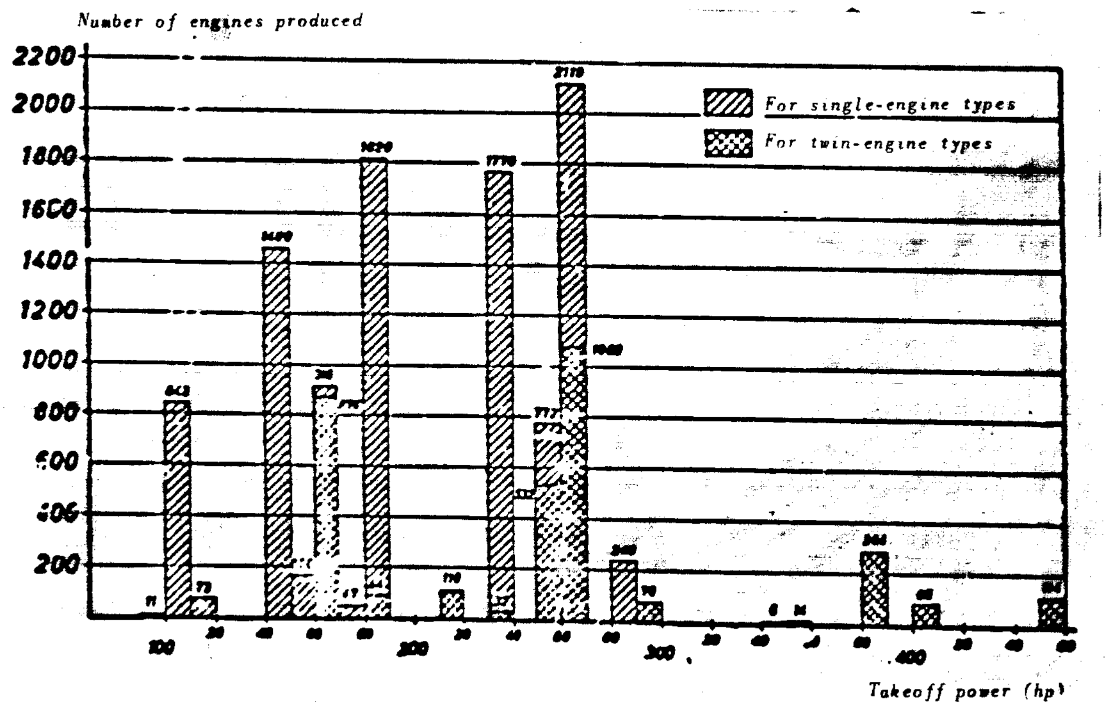
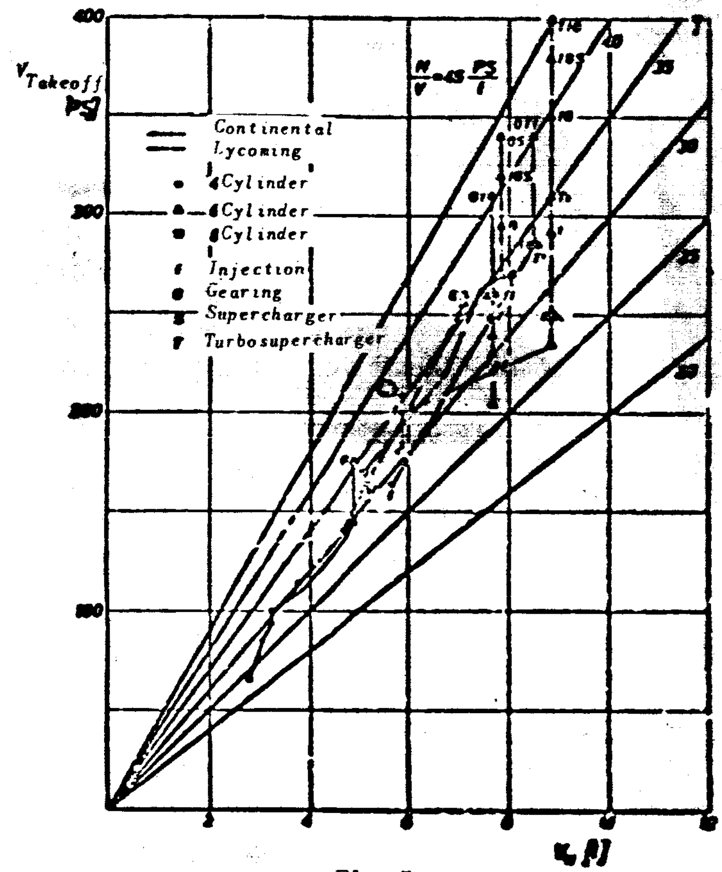
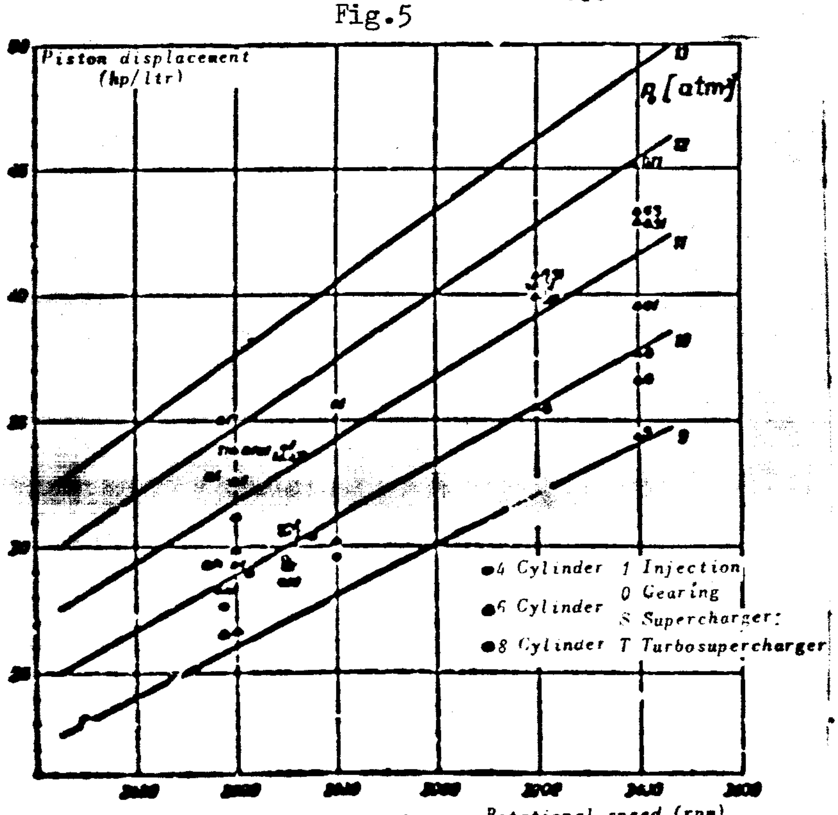

Number of engines produced
For single-engine types
For twin-engine types
Takeoff power (hp)

Fig.4



$V_{Takeoff}$ PS
$\frac{N}{V} = 45\ \frac{PS}{l}$
Continental
Lycoming
4 Cylinder
6 Cylinder
8 Cylinder
Injection
Gearing
Supercharger
Turbosupercharger

Fig.5



Piston displacement
(hp/ltr)
p_e [atm]
4 Cylinder
6 Cylinder
8 Cylinder
I Injection
O Gearing
S Supercharger;
T Turbosupercharger
Rotational speed (rpm)

Fig.6

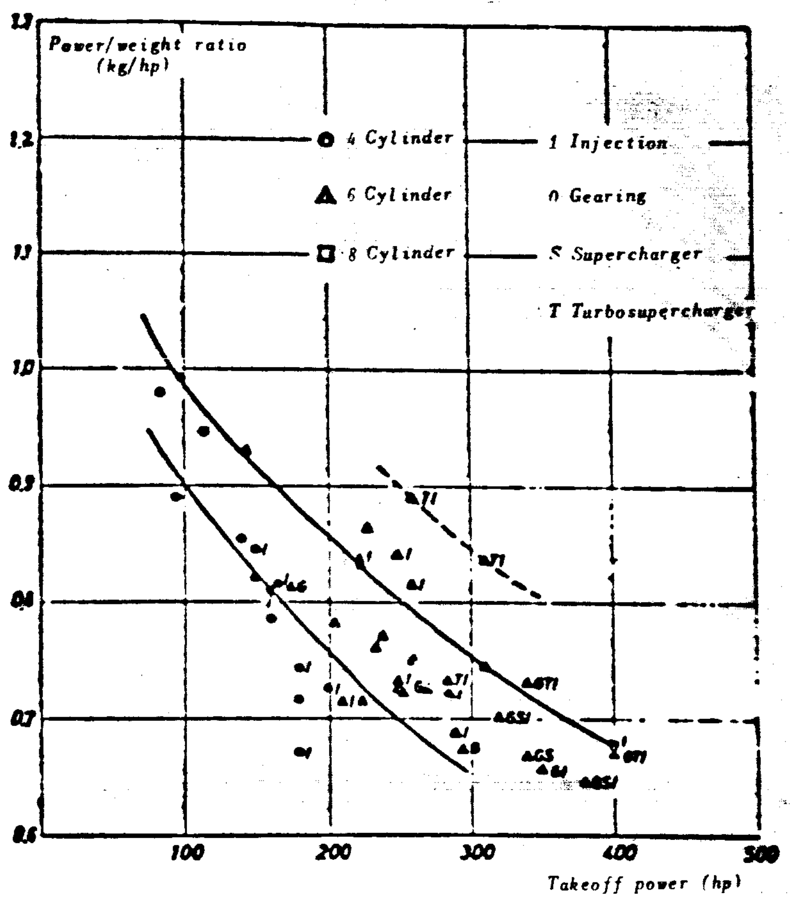

Power/weight ratio (kg/hp)
4 Cylinder
6 Cylinder
8 Cylinder
1 Injection
G Gearing
S Supercharger
T Turbosupercharger
Takeoff power (hp)
100
200
300
400
500

Fig.7

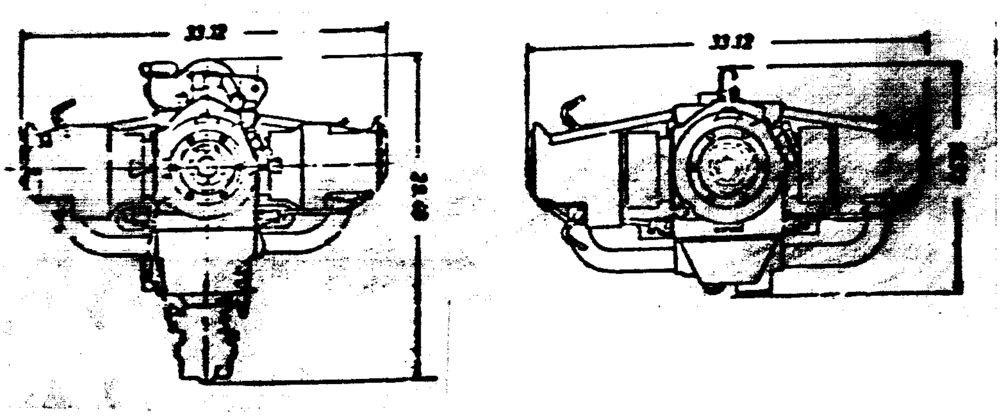


Fig.8

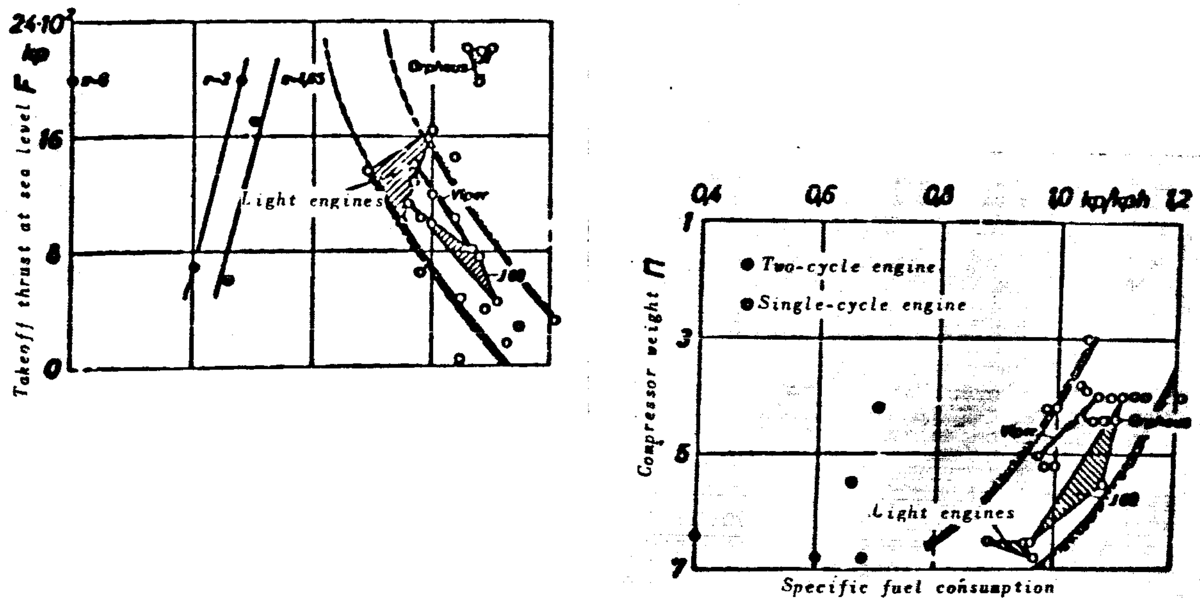

Takeoff thrust at sea level F
Light engines
Orpheus
Viper
J60
Compressor weight Π
Two-cycle engine
Single-cycle engine
Light engines
Viper
Orpheus
J60
Specific fuel consumption

Fig.9

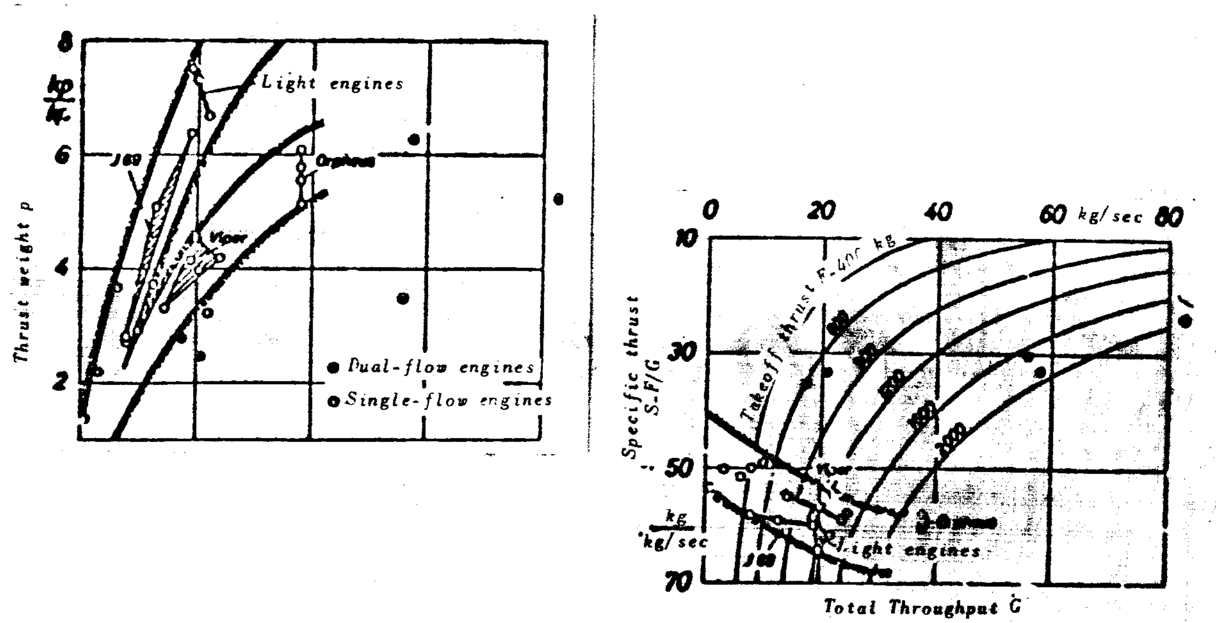
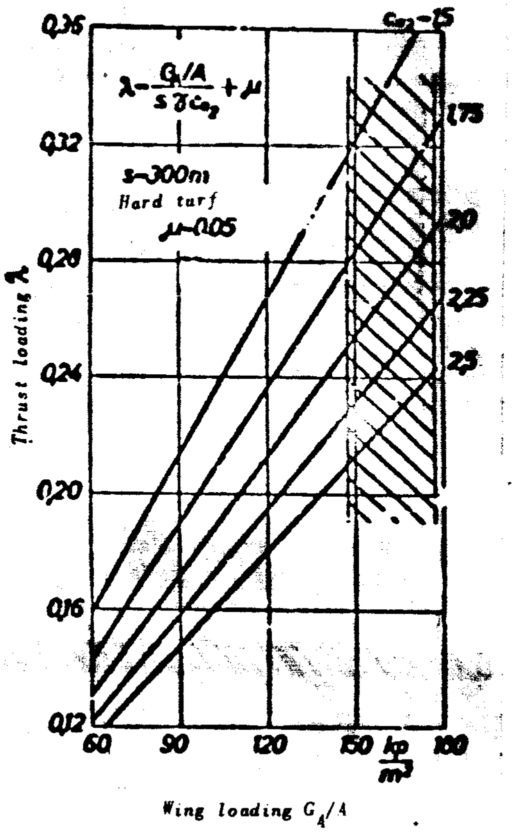
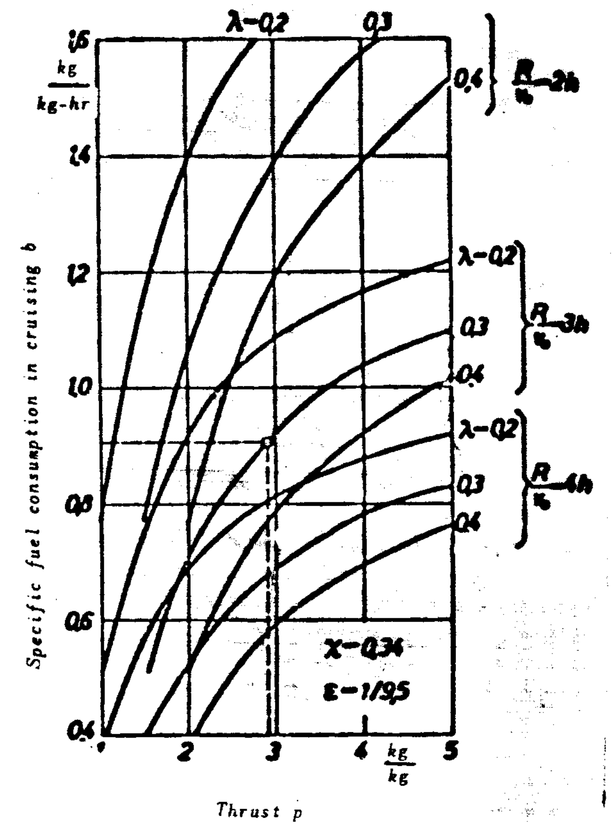

Thrust weight p
Light engines
J60
Orpheus
Viper
Dual-flow engines
Single-flow engines
Specific thrust S-F/G
Takeoff thrust
Viper
Orpheus
Light engines
J60
Total Throughput Ġ

Fig.10



Thrust loading λ
Wing loading G_A/A
s=300m
Hard turf
μ=0.05

Fig.11



Specific fuel consumption in cruising b
Thrust p
kg/kg-hr
kg/kg

Fig.12

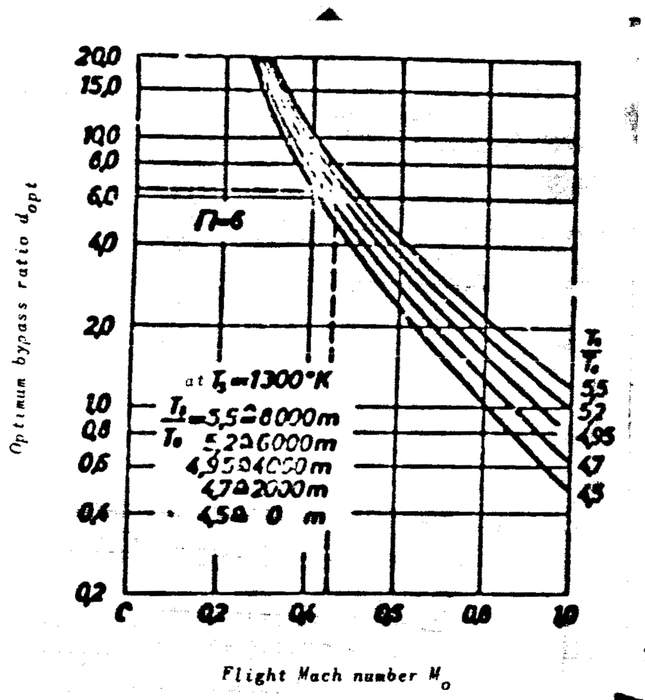

Optimum bypass ratio d_{opt}
Flight Mach number M_o
at T_3=1300°K
$\frac{T_3}{T_0}$=3,5≙8000m
5,2≙6000m
4,95≙4000m
4,7≙2000m
4,5≙ 0 m

Fig.13

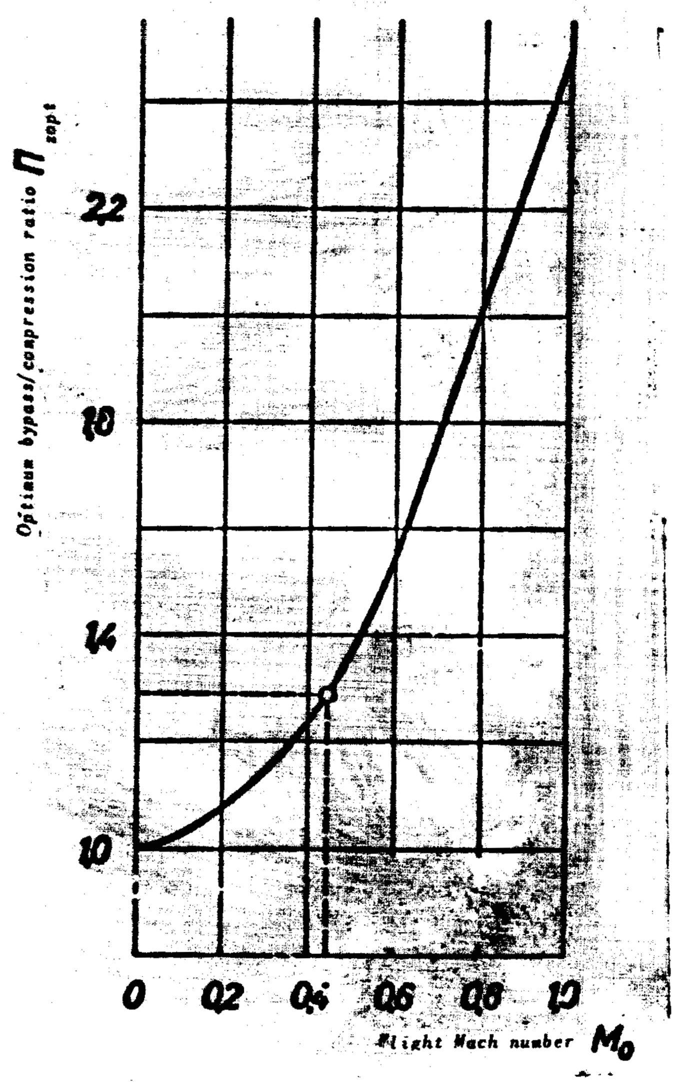

Optimum bypass/compression ratio Π_{zopt}
Flight Mach number M_o

Fig.14

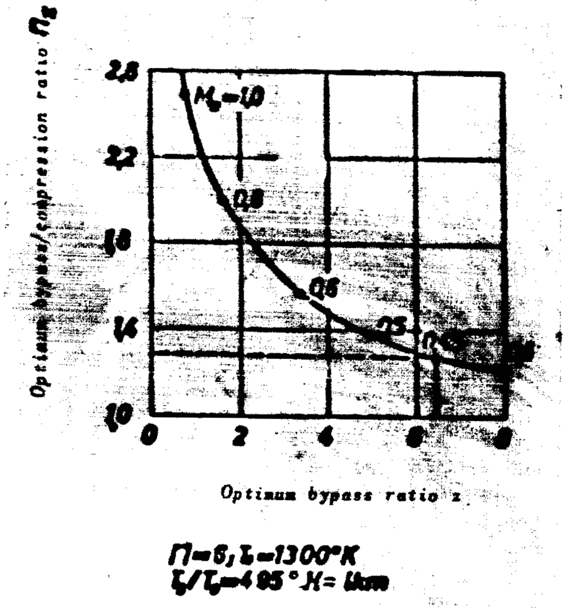

Optimum bypass/compression ratio Π_z
$M_0=1.0$
0.8
0.6
0.3
Optimum bypass ratio z
$\Pi=6;\ T_3=1300°K$
$T_3/T_0=4.85°\ H=4km$

Fig.15

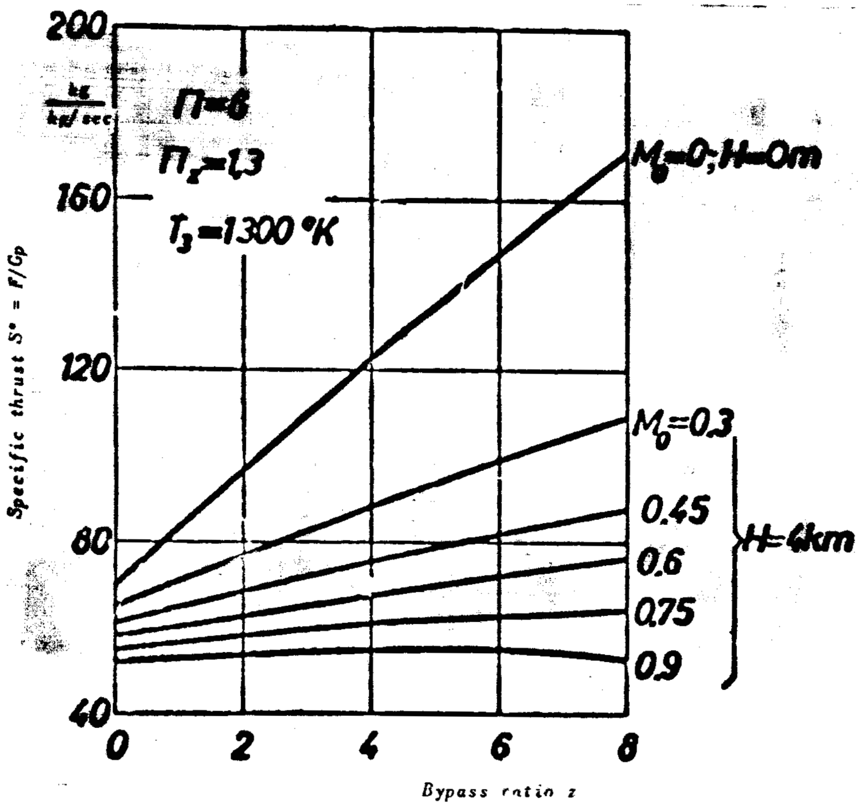

$\Pi=6$
$\Pi_z=1.3$
$T_3=1300°K$
Specific thrust $S° = F/G_p$
kg / kg/sec
$M_0=0;H=0m$
$M_0=0.3$
0.45
0.6
0.75
0.9
H=4km
Bypass ratio z

Fig.16

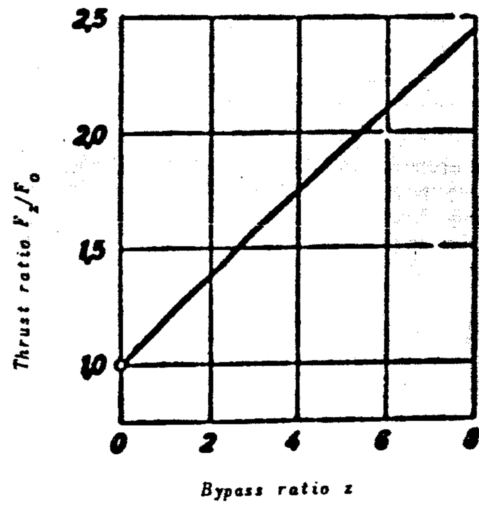

2,5
2,0
1,5
1,0
0
2
4
6
8
Thrust ratio F_z/F_o
Bypass ratio z

Fig.17

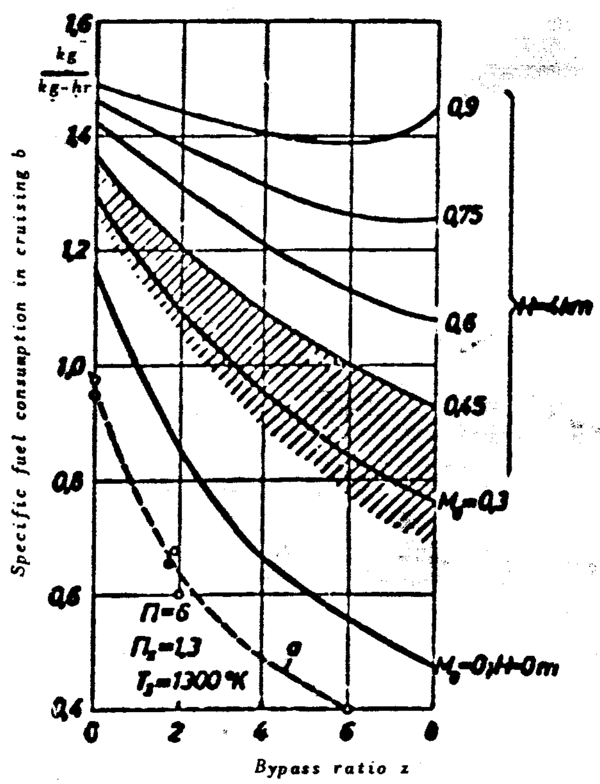

1,6
kg/kg-hr
1,4
1,2
1,0
0,8
0,6
0,4
0
2
4
6
8
0,9
0,75
0,6
0,45
M_0=0,3
M_0=0;H=0m
H=
Π=6
$Π_z$=1,3
T_3=1300°K
a
б
Specific fuel consumption in cruising b
Bypass ratio z

Fig.18

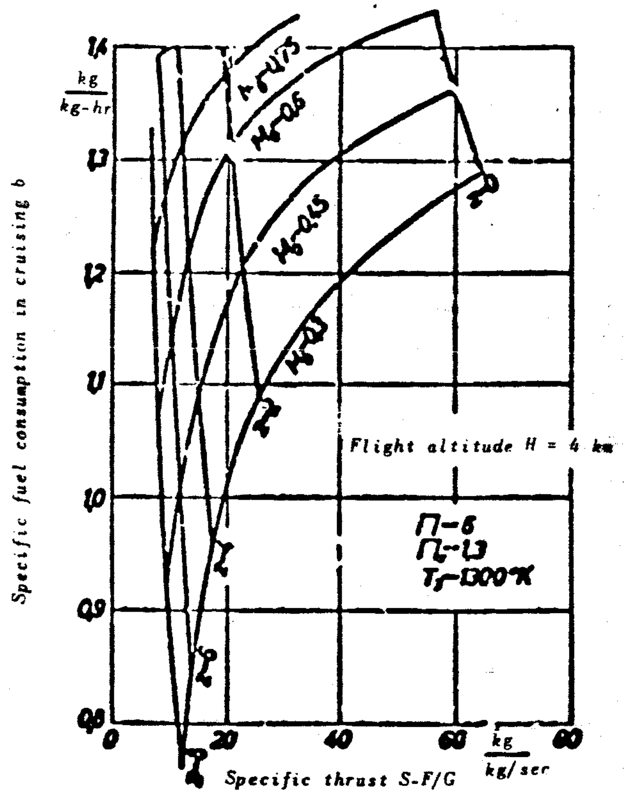

Specific fuel consumption in cruising b
kg/kg-hr
Specific thrust S-F/G
kg/kg/sec
Flight altitude H = 4 km
T_r-1300°K

Fig.19

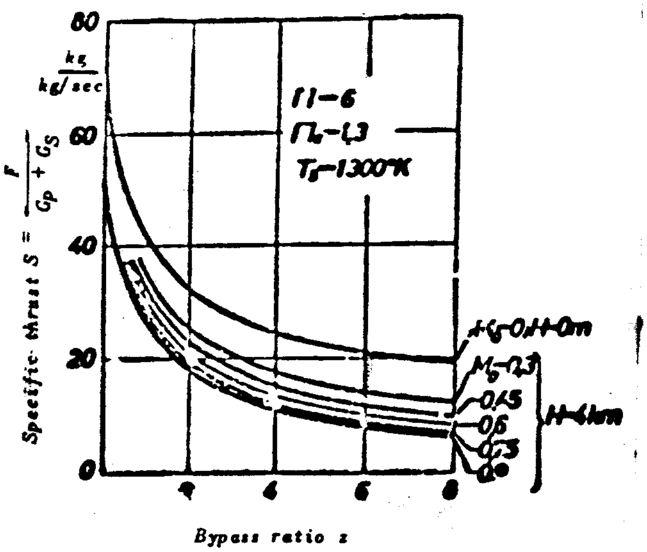

Specific thrust S = F/(Gp + Gs)
kg/kg/sec
T_r-1300°K
H=4km
Bypass ratio z

Fig.20

/46

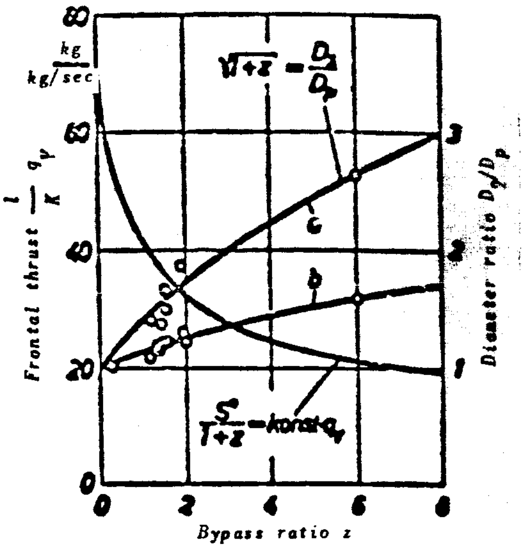


Fig.21

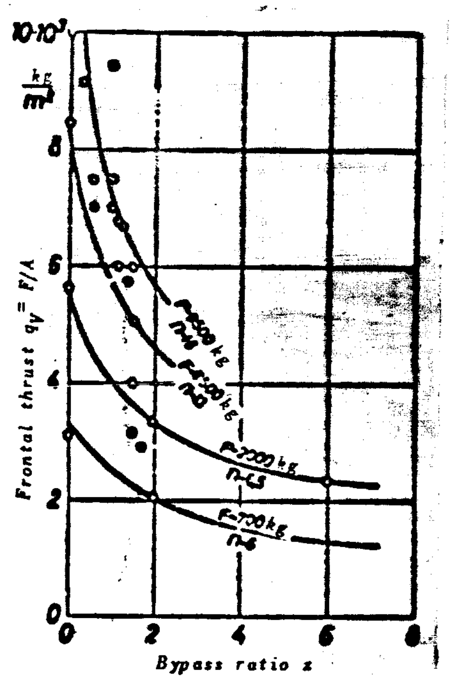
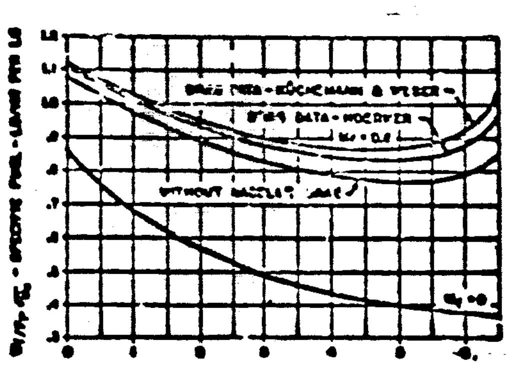


Fig.22



illegible!

Fig.23

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